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Design Studies of the LHC Beam Dump

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Summary

A beam dumping system is being designed at CERN for the Large Hadron Collider (LHC), whose purpose is to remove safely from the machine the two circulating proton beams. The system will extract the beams from the LHC ring in 86 μs and direct them onto two external dumps, which will absorb the beam energy.

In the baseline design, each beam dump consists of consecutive carbon cylinders for a total ϕ700×7000 mm, shrink-fitted into a 940×940 mm solid aluminium frame, water-cooled by an external base plate. Beam absorption will cause an adiabatic, in depth temperature rise of the carbon cylinders. The resulting severe thermal expansion is partly impeded by mass inertia, and gives rise to thermal-shock stress waves, which propagate through the structure.

The thermal shock behaviour of the dump core has been studied under linear-elastic assumptions. Results are presented in this paper, and a procedure is outlined to analyse the mechanical transients of similar structures.

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1. Introduction

A beam dumping system is being designed for the Large Hadron Collider (LHC), whose purpose is to remove safely from the machine the two circulating high-energy proton beams. The system will extract the beams from the LHC ring in 86 μs and direct them onto two external dumps (TDEs, or Target Dumps External), which will absorb the beam energy [1]. The dumps must be ready for beam abort at any phase of the collider operation, so that no dumping frequency is specified. Nevertheless, a nominal delay of 8h between two aborts is foreseen, which corresponds to the expected time between two LHC fillings.

In the baseline design, each beam dump core (ø700×7000 mm) consists of consecutive carbon cylinders of two different densities, shrink-fitted into a 940×940 mm solid aluminium frame, water-cooled by an external base plate (Fig. 1). The dumped beam is diluted in order to reduce to an acceptable level the maximum deposited energy density in carbon. A deflecting system provides this dilution by sweeping the beam along an *e*-like path on the upstream face of the core (Figs 1, 3).

This design has been preliminarily substantiated by Monte Carlo simulations of particle cascades [2] and heat transfer analyses [3]. The present paper is devoted to the mechanical analysis of the thermal shocks which occur in the beam dump.

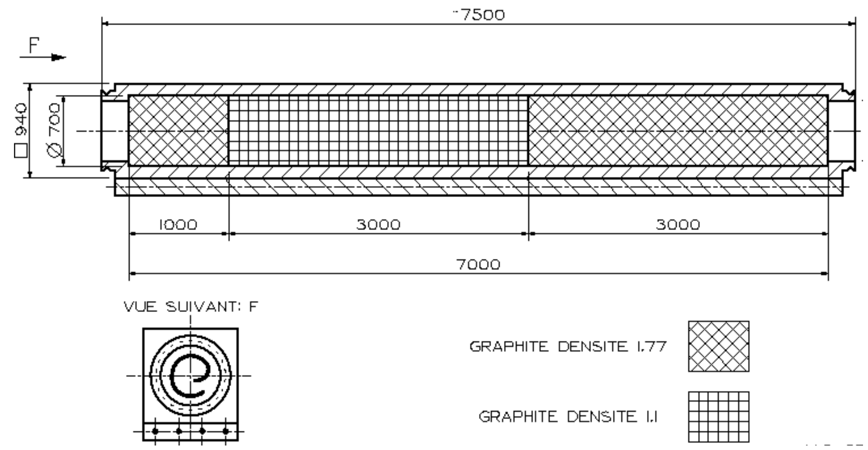

Figure 1: Schematic view of the LHC beam dump baseline design.

2. Analysis approach

The choice of a well suited analysis approach has been the first problem to be solved in the thermal shock analysis of the LHC beam dump.

2.1. Thermal shock

When a proton beam is dumped onto the TDE, a thermal stress field arises which results from three components: the possible quasi-static stresses due to an inhomogeneous residual heat of previous beam aborts, the dynamic stresses caused by the just aborted beam (the thermal shock), and the quasi-static stresses left by the just aborted beam after the shock is damped out.

Due to the nominal delay of 8h between two consecutive beam aborts, the first stress component has been neglected. For the rest, the thermal load of the just aborted beam is active over a period (86 μs), which is not long enough to reach stress equilibrium. The thermal expansion is therefore partly prevented by the mechanical inertia, and gives rise to transient stress waves which propagate through the cylindrical dump core radially (transversal waves) and axially (longitudinal waves).

2.2. Analythical model

The thermal shock behaviour of cylindrical beam obstacles has been subject of investigations at CERN for many years; targets, windows and beam absorbers, in fact, often resemble a circular cylinder.

Transient wave motions with axial symmetry are nevertheless difficult to analyse, as a simple general solution for cylindrical waves is missing [7]. Many of the solutions have been, therefore, worked out under simplifying assumptions for several load cases and boundary conditions.

Unfortunately, these simplifying assumptions are not applicable to the LHC beam dump because of the beam sweeping; in fact, the thermal load in the cylindrical dump core is not axi-symmetric. The radial and tangential displacements u_r and u_θ are therefore intimately coupled in the propagation of transversal waves. Moreover, the radial dimension of the cylindrical core is not negligible, and the heating is highly localised along the sweep path. Longitudinal waves are, therefore, not purely axial motions; they have a radial component which make them diverge as they propagate.

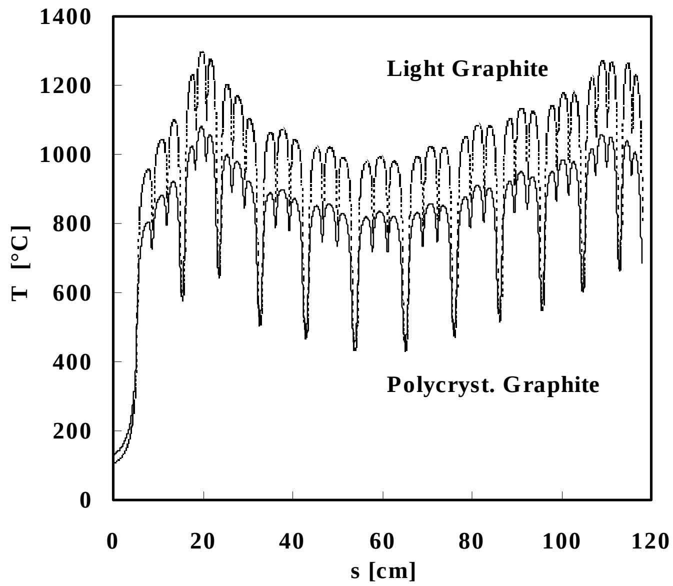

Figure 2: Adiabatic temperature distribution along the sweeping path, at depth z_{max} .

As no analytical solution is available, a numerical approach has been adopted, which relies on the use of finite element procedures.

3. Numerical model

3.1. Geometry

The study has been focused on the most loaded carbon cylinders of the dump core. The aluminium frame has not been modelled and the mechanical contact between frame and core has been neglected.

The outer surface of the cylinder has been left free to vibrate and to reflect the stress waves. All the elastic strain energy remains, therefore, contained within the cylinder. Moreover, because a compressive wave is reflected at a free surface as a tensile wave, resulting stress conditions are expected to be conservative.

Two finite element models have been analysed; a “cross section” model of the carbon cylinder, and an axi-symmetric model.

The cross section model is intended to represent a generic section of the cylinder away from its axial ends (plane strain) or very close to them (plane stress). It allows the study of the radial stress waves, tracking their superposition and reflection at the free circular edge.
The axi-symmetric model is a partial, local model, which is intended to study the longitudinal stress waves. It has a radius of 14 cm, which approximates the minimum distance between the swept beam and the lateral cylindrical edge.

3.2. Load

As the TDEs will be a permanent equipment of the collider, the ultimate foreseen beam intensity ($4.8 \cdot 10^{14}$ protons of 7 TeV, [4]) is to be considered, which corresponds to an energy of 540 MJ. This thermal load has been thoroughly studied in Refs [2, 3]. Hereinafter, the main conclusions from these studies will be recalled.

The beam particles are lumped into 2835 “bunches”, further grouped into 35 “trains” of 2 μs. Each bunch has an initial trajectory approximately parallel to the dump axis and produces a particle cascade which opens as a cone within the material. Correspondingly, a diverging region of approximately conical shape is heated up in the carbon core. Two parameters determine the maximum heat load; the overlapping of the cascades, and the axial depth z. As the cascades diverge, in fact, the heated zones of neighbouring bunches overlap, so that they add their heat contribution. Within each cascade, moreover, a maximum energy deposition is reached at a depth (z_{max}) which is a function of the material properties. The maximum energy deposition increases with material density.

This thermal load is active over the beam extraction period (86 μs), which is much shorter than that required for heat conduction (~ 0.01 s). Beam absorption causes, therefore, a practically adiabatic heating, so that the temperature rise may be evaluated without any thermal analysis, by means of the (temperature dependent) specific heat. Figure 2 displays the adiabatic temperature distribution along the sweep path for the two carbon materials at their depth z_{max}. The 35 bunch trains are clearly visible. The maximum temperature rise is limited to about 1300 °C in the light graphite, and to 1100 °C in the polycrystalline graphite.

3.3. Space and time discretization

In solving a dynamics problem by the finite element method, the selection of an appropriate element length L_e and of the time step Δt is fundamental to accurately represent the travelling waves [5] (§ 9.4.4).

If L_w is the critical wave length to be represented, t_w the total time for this wave to pass a point, c the wave speed, and if n time steps are necessary to represent the travel of the wave, then $\Delta t = t_w / n$ and the "effective" length of a finite element should be $L_e = c\Delta t$. The relation between L_e and the actual element size depends on the numerical procedure used by the finite element code to integrate the differential equations of the dynamic problem. For the implicit, unconditionally-stable time integration method adopted by ANSYS (Refs [5, 6]), L_e may be taken equal to the smallest distance between any two adjacent nodes that lie in the direction of the wave travel.

In practice, the critical wave length L_w may be inferred by a Fourier analysis of the loading function. The distribution and frequency content for the thermal load on the LHC beam dump, approximated as a ramp over 2 μs, gives a spectrum of frequencies centred around 1 MHz. The corresponding 1 μs wave period, and the longitudinal wave speed of ~2400 m/s for carbon, give a tentative value of ~2.4 mm which has been confirmed by numerical results.

Table 1: Graphite properties at 20 °C

Property	Units	Isotropic Polycrist.	Flexible
Density	g/cm^3	1.77	1.1
Specific heat	J/g°C	0.65	0.69
Thermal conductivity	W/m°C	75	$160_{\parallel}$ / $4_{\perp}$
Lin. thermal expansion	10^{-6}/°C	3.5	$\sim 0_{\parallel}$ / $28_{\perp}$
Young Modulus	GPa	9.2	1.4
Poisson's ratio	-	0.15	0.1
Tensile strength	MPa	28	4.5

3.4. Boundary conditions

The dump core has been assumed to be simply supported. In the cross section model, three degrees of freedom have been suppressed by preventing translation of three nodes along three non intersecting directions. It is important to apply all these constraints at nodes located on the boundary, as any fixed degree of freedom within the model interferes with the travelling stress waves.

Plane stress and plane strain conditions have been investigated. For plane strain, three possibilities are available: the cross section may be constrained in translation (no axial expansion) and rotation (no bending), allowed to translate but not to rotate, or allowed to translate and rotate. In the present study, the difference between these three cases is negligible, as the adiabatic mean temperature is close to the 20 °C reference temperature for thermal expansion. The temperature distribution is moreover centred on the dump core, so that no thermal bending is expected in the short-term analyses.

In the axi-symmetric model, only half of the carbon cylinder has been studied. In this case, the boundary condition of no axial displacement on the axial symmetry plane $z = 0$ mm is sufficient to simply support the model and to allow free vibration. Two conditions have been analysed: free axial expansion and no axial displacement.

Seven cases have been considered: *1)* Free *z* steady-state; *2)* Plane strain steady-state; *3)* Free *z* transient; *4)* Plane strain transient; by combining these four cases, it is possible to separate the effects of the stress waves: *5)* Steady-state surface effect = case *1* –case *2*; *6)* Radial + axial wave without steady-state components = case *3* – case *1*; *7)* Axial wave without steady-state component = – case *1*+ case *2* + case *3* – case *4*.

3.5. Material

Two carbon materials have been selected: isotropic Polycrystalline Graphite (PG) and light, Flexible Graphite (FG) (Table 1). Both have a good resistance to thermal shock and are stable under repetitive heating cycles up to 2500 °C in absence of oxygen. As their behaviour is not symmetric in tension and compression, the Stassi (generalised Von Mises) stress norm has been used to investigate material failure. It is noteworthy that hydrostatic tensile states are in this way limited.

The materials are supposed to be homogeneous and linear elastic. In a conservative approach, damping of the stress waves has been neglected.

4. Results

4.1. Transversal waves

The sudden heating generates two primary radial stress waves: an inner wave inside the sweep path, and an outer wave outside of it (Fig. 3). The inner wave converges rapidly to the centre, where it starts collapsing at about 45 μs. The outer wave forms an approximately elliptical front which is not centred on the core axis; this wavefront propagates outwards and is first reflected at ~90 μs at the free boundary.

These two primary radial waves are of compressive hydrostatic nature. Together with the quasi-static hot compressed zone localised along the sweep path, they form the early stress distribution. Later, collapsing of the inner wave and reflection of the outer wave cause an increase of the Stassi stress; in both cases, in fact, stresses become tensile and a positive hydrostatic pressure arises. The use of FG graphite between upstream and downstream PG graphite is necessary to keep this pressure at an acceptable level.

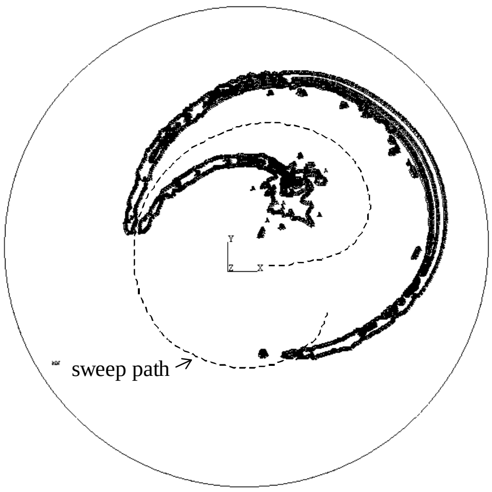

Figure 3: Primary transversal stress waves at 51 μs.

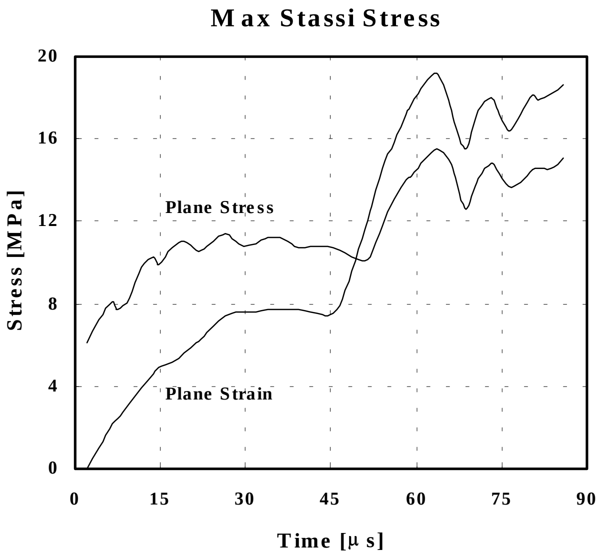

Figure 4: History of the maximum Stassi stress from radial waves in the polycrystalline graphite.

For the PG, the history of the maximum Stassi stress due to the radial waves is depicted in Fig. 4. After an initial rise during the first ~20 μs, the maximum stress remains constant until ~45 μs, when a second steep increase is noticed until ~65 μs. At this time, the maximum stress is attained in plane stress and in plane strain. Later, oscillations occur at a lower stress level.

In the FG, no significant transverse wave is generated due to the negligible in-plane thermal expansion. Stassi stresses up to 13 MPa are found in plane strain, while the stress values remain below 1 MPa for plane stress conditions.

4.2. Longitudinal waves

The longitudinal stress wave has a conical shape, with a vertex located at the hottest point on the free axial surface of the carbon cylinder. As the wave propagates, the maximum Stassi stress occurs on the axial symmetry plane of the cylinder when the two longitudinal waves coming from opposite directions overlap. The maximum stress value is attained for small thicknesses. It decreases for thicker cylinders, approaching the asymptotic value of the plane strain case for thicknesses ≥ 50 cm.

4.3. Structural response

The longitudinal wave caused by a single train has been extracted following the procedure outlined in Sec. 3.4 (case *7*) and superimposed on the transversal waves for all the 35 trains.

The PG will be used in cylinders of thickness ≥ 50 cm, in which the longitudinal wave is dispersed enough to leave the radial stress wave only. The maximum thermal shock stress is of 18 MPa, which is within the allowable value of 20 MPa.

The FG will be used in the form of thin plates (thickness ≤ 10 mm). In this case the plane stress assumption is valid, which results in stresses ≤ 1 MPa, that is below 1/3 of the tensile limit.

5. Conclusion

Based on this study, the core of the main LHC beam dump is being built by consecutive polycrystalline graphite (PG) cylinders and flexible graphite (FG) plates. A 1 m long section of PG is followed by 3 m of FG, and again by 3m of PG. The maximum temperature increase is limited to 1300 °C in the FG, and to 1100 °C in the PG. Thermal shock stresses are within acceptable limits.

6. Acknowledgement

The authors sadly have very much in mind the loss of their colleague Jan Zazula, who disappeared in September 1997 on the ‘glacier de Charpoua’ near Chamonix (France) pursuing his favourite passion for the mountain, while he was strongly and enthusiastically involved in the first studies of the LHC beam dump [2, 3].

The major contribution of Paola Sala-Ferrari in the optimisation of the carbon density along the dump axis should be underlined.

7. References

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